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The copper-doped p-Ge THz laser in the Voigt configuration: possibility of mode-locked operation

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***Abstract* - We have constructed a copper-doped germanium hot hole THz laser and studied its performance under normal - pulsed - operation, in order to investigate the possibility to create very short "quasi monochromatic" pulses through active mode-locking. The E and B field region for which normal "long pulsed " laser emission occurs, emission wavelength as a function of B field and the temporal shape of the laser pulse have been studied. The results indicate that the performance of this Ge:Cu crystal can not yet compete with that of an earlier studied Ge:Ga laser under similar conditions. Nevertheless active mode-locking has already been observed.**

I. INTRODUCTION

The p-Ge hot hole laser is a solid state laser with a strong and tunable Terahertz emission [1]. The acceleration of holes in crossed electric- (E) and magnetic- (B) fields at cryogenic temperatures leads to population inversion either between the light- and heavy hole band, leading to intervalence band lasing, or between subsequent light hole Landau levels (cyclotron resonance lasing). We have shown recently that mode locked operation of such a laser can be achieved by applying an ac electric field *parallel* to B at half the cavity round trip frequency. Quasi monochromatic THz pulses as short as 60 ps have been created with that technique [2,3,4].
Most of the investigations on the p-Ge laser have been performed on Ga doped material. However, the ionization energy of this single acceptor is about 11 meV, and the finite population of the acceptor levels under lasing conditions results in strong absorption of emitted light, leading to a large gap in the laser emission around 75 cm^{-1}. Moreover it has been proposed that laser emission at certain wavelengths would be intimately related to the presence of these acceptor levels, interfering therefore with easy wavelength tunability. [5] The presence of different kinds of laser levels possibly also causes the peculiar time dependence of the emission wavelength during a laser pulse, that was found to complicate the creation of reliable mode locked pulse trains [4].
To avoid the gap in the emission spectrum, recently the double acceptors Be and Zn, and the triple acceptor Cu have been used as dopants [6,7]. Because the ionization energies of those acceptors is larger than the highest emission energy of the Ge laser, they should not in any way interfere with the laser action. Although, the experimental evidence so far seems to indicate that Ge:Be is the best laser material, we have chosen to explore in more detail the Ge:Cu material. The reason for that being the fact that copper doped Ge can easily be fabricated in many different concentrations by simple diffusion of copper in pure Ge, whereas Ge with other dopants have to be Czochralski-grown from a doped melt. That offers a good opportunity for a detailed optimization study of this laser, for (quasi-) CW as well as for mode locked operation.

II. SAMPLE FABRICATION

As starting material we have used a 5 mm thick slice, perpendicular to (100), of Czochralski-grown ultra-pure germanium from Union Minière Electro-Optical Materials. It has a dislocation density of less than 3000 per cm^2 and a p-type impurity concentration of less than 10^{12} cm^{-3}. For the fabrication of the doped samples we followed the recipe outlined in reference [7].
Hall effect samples (1x5x7mm^3) to test the Cu diffusion technique in the system set up at Delft University were prepared, with crystal faces normal to the (100), (011) and (0 -11).
Also a 5x7x10mm^3 bar-shaped sample for a preliminary study of stimulated emission was made, with the HV contacts such that E // (011). For the final laser performance study a 5 x7x50mm^3 sample was made (see Fig. 1.), the same size as the Ge:Ga sample on which earlier pulsed and mode lock experiments were

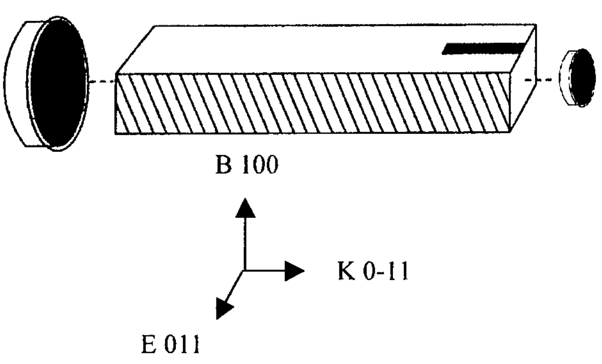

Fig. 1: Sample + cavity.

performed [2,3,4]. The copper diffusion for both lasing crystals was performed at 700 °C for 24 hours, because our results on the Hall samples showed that in that case the resulting copper concentration, after rapid quenching of the crystal to room temperature, would be about 1.5×10^{15} cm^{-3}.
After diffusion, the sample was polish-etched and the 5x7 end faces were made parallel to each other within 30''. The high voltage excitation contacts, covering the full 5x50 sides, and the 1x10 modulation contacts at the 7x50 surfaces, were made from gold on palladium, after boron implantation. Etching could not be used to define the electrical contact areas, as it destroys the optically polished end faces. Therefore, during implantation and evaporation, the *non-contact* areas were covered with pieces of silicon wafer. In order to remove implant damage and fully activate the boron, the samples were given a post-implant anneal. Copper wires were soldered on the contact areas with Indium.

III. EXPERIMENTAL SET UP

The small laser crystal with only HV contacts and no external cavity was mounted in a Helium cryostat in the bore of a superconducting solenoid.. Experiments were performed with the B-field in various directions with respect to the crystal axis, but keeping B always perpendicular to E. Emission under pulsed HV excitation was measured with a fast cryogenic Ge:Ga detector, placed near to the laser crystal.
The large laser crystal is mounted in a cryostat with tail window . Two flat gold mirrors evaporated on quartz substrates, are pressed to the end faces and isolated from the crystal by 10 µm Teflon films, to form a simple cavity. The crystal is studied in the Voigt configuration, i.e. both E // (011) and B // (100) are perpendicular to the (0 -11) optical axis of the laser cavity, see Fig. 1. The diameter of one of the cavity mirrors is smaller than the end face, and light leaking out alongside this mirror, through the cryostat window, is detected using a variety of room temperature detectors. Instead of this small outcouple mirror, also a capacitive outcouple mesh has been used to enable the observation of the light emitted across the full end face of the laser crystal [8]. This results also in a larger signal intensity.
The magnetic field, generated by a homogeneous room temperature electromagnet with a maximum field of 1.3T, can be rotated with respect to E to optimize lasing conditions. Both the HV excitation field and the RF modulation field are applied in pulses of a few microseconds long to avoid excessive heating of the crystal.
The THz emission is studied using either a relatively slow pyroelectric detector, or a very fast mm-wave Schottky diode or a GaAs/AlGaAs heterostructure detector. Using a simple reflection grating set up, the wavelength of the emitted light can be measured. The signals are monitored with either a 500 Mhz digitizing oscilloscope scope or with a single shot 6 GHz bandwidth oscilloscope.

IV EXPERIMENTAL RESULTS

The experiments on the $5 \times 7 \times 10 mm^3$ crystal reveal pulsed THz emission that follows closely the high voltage excitation pulse, see fig. 2. As evident from fig. 3, the emission also shows the peculiar dependence on the applied E and B field, with a maximum intensity centered around an E/B ratio of about 1.3kV/T. Those observations prove that the emission is not due to ohmic heating of the crystal, which increases monotonously towards higher E and B fields, but originates from the population inversion created by the crossed E and B

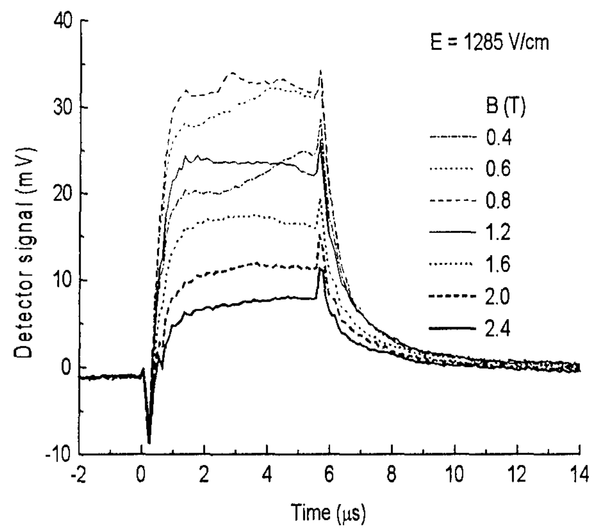

Fig. 2: Pulsed (spontaneous ?) emission from the small laser crystal.

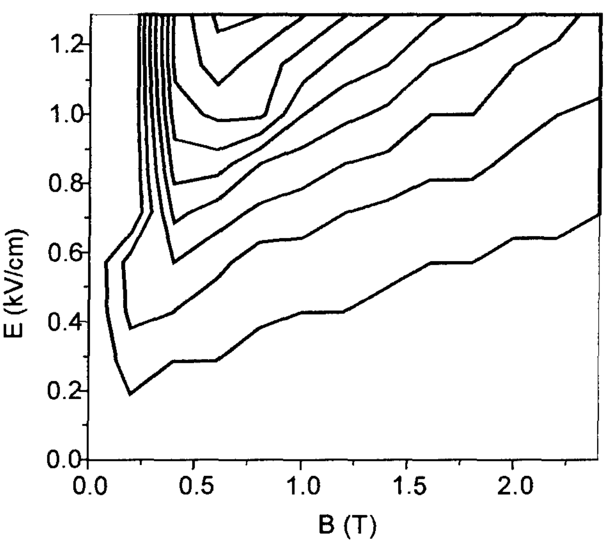

Fig. 3: E-B emission region of small crystal ; each contour line is a 4 mV signal increase ranging from 4 to 36 mv.

field excitation. In view of the rather low signal intensities and the absence of sharp emission boundaries, we deal here most probably with spontaneous rather than with stimulated emission. This result shows that the low temperature density of ionized

acceptors is of the right order of magnitude- $\approx 10^{14}\ cm^{-3}$, about 7% of the Cu density [7] - to create population inversion.
Introductory experiments on the 5 x7x50mm^3 sample were performed also using a Ge:Ga detector near the crystal. In fig. 4 the pulsed emission signals at B=0.9T and E=1.4kV/cm are shown for various directions of B; a clear minimum of the delay between start of HV excitation pulse at t=0 and start of laser action, together with the steepest growth of signal intensity is seen for $\varphi \approx 4^o$. This direction, for which E and B are perfectly perpendicular, is independent of the magnitude of B, showing the absence of a "parallel Hall" effect, as observed earlier in Ge:Ga crystals cut along low symmetry crystal directions.

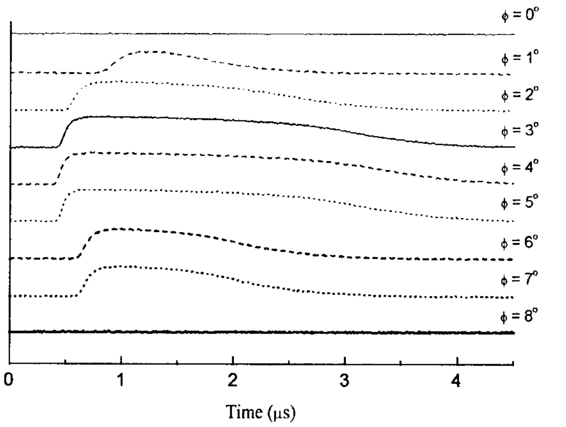

Fig. 4: Shape of the emission pulse as function of the direction of B and E.

In fig. 5 the E/B field region is shown for which stimulated emission is observed using a room temperature pyroelectric detector. With the mirror outcoupler, a smaller emission region is observed than with the mesh outcoupler, just as was found earlier for the Ge:Ga laser [8]. The E/B ration for the emission region agrees with expectations [7].
In fig. 6 emission spectra with a resolution of about 2 cm^{-1} are shown for a few B fields. Although these spectra differ from those reported by Reichertz et al [9]

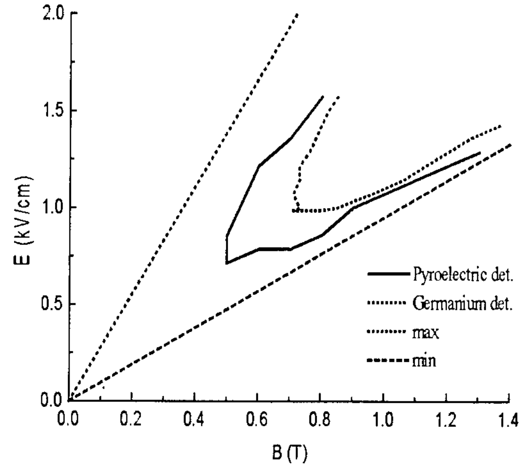

Fig. 5: E-B field region of laser action.

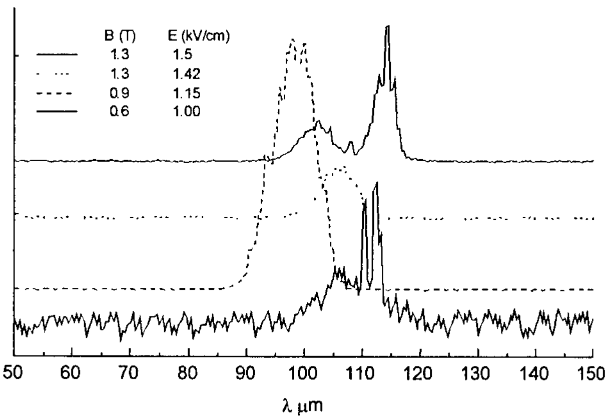

Fig. 6: Emission spectra at various B fields.

for the Be and the Cu doped Ge lasers - operated in the Faraday configuration - it is conceivable that the broadband emission originates from intervalence band transitions. It is to be investigated whether these spectral differences stem from the different laser configurations used.
Some preliminary time resolved experiments have been performed. The peculiar pulse shape shown in fig. 7 strongly resembles those observed in the Ge:Ga laser and suggests that also in the Ge:Cu system a variation in emission wavelength *during* the laser pulse occurs. The intensity variations on a 25 ns timescale are related to beating between different transverse laser modes.

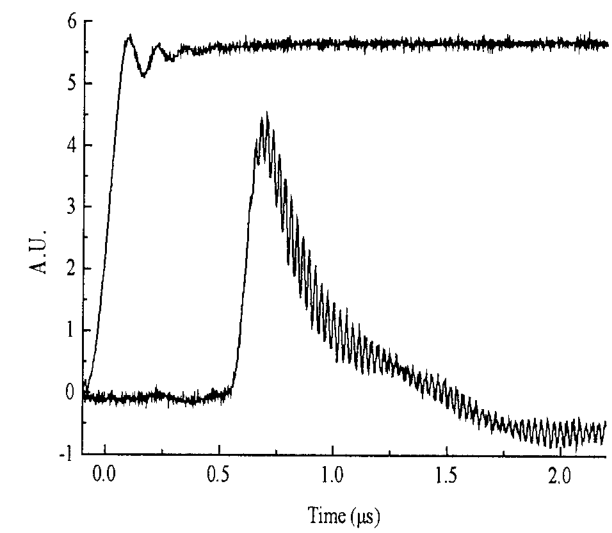

Fig. 7: Time resolved laser output at B=0.78 T observed with a fast Hetrostructure detector and the high voltage pulse.

In general, it is found that in this Ge:Cu laser the time delay between start of the high voltage excitation and start of laser action is larger, the small signal gain is smaller, and the maximum pulse duration is shorter than observed in the Ge:Ga laser. Moreover lasing action starts at a larger B field. So, these first data on long pulsed operation indicate that lasing conditions in this

crystal are less favorable than in our earlier reported Ge:Ga crystal. Experiments on other Ge:Cu crystals, also with different Cu concentrations, have to be performed to reach a more general conclusion on this point.

We have applied an RF electric field to the modulation contacts at half the cavity roundtrip frequency, to modulate the laser gain at the round trip frequency, a necessary prerequisite for mode-locking. Inspection of the electronic system showed that the Q-value of the circuit involving the modulation contacts was rather low, possibly preventing the RF field to reach its optimum value. It is not clear whether this is due to bad contacts or to an intrinsic material property. Nevertheless, in these first experiments we have succeeded in operating this laser under mode locking conditions. In fig. 8 a typical result of the optical output is given. A train of pulses at a 1.3 ns time interval, the cavity roundtrip time, is observed. However, the modulation depth is not very large; Improving on the amplitude of the RF field might possibly lead to better results and shorter pulses.

In summary we have shown that the copper doped germanium laser can be operated under mode-locking conditions; the present overall performance, however, does not yet equals that of the Ge:Ga laser.

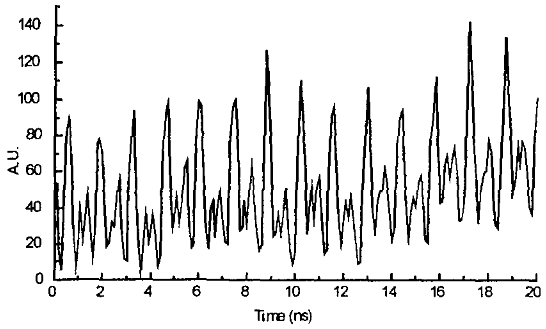

Fig. 8 Pulse train under mode-locking conditions. The 1.3 ns pulse separation equals the cavity roundtrip time.

Acknowledgement

This work is part of the research program of the European TMR Network "InterEuropean Terahertz Action (INTERACT)". The authors thank the group of prof. Renk at the Regensburg University, Germany for the use of their GaAs/AlGaAs heterostructure detector and M.J. Vermeulen, Delft Interfacultary Reactor Institute, for the use of the 6-GHz scope.

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